19TH EXOTIC BEAM SUMMER SCHOOL (EBSS2022)

Argonne NATIONAL LABORATORY

Nuclear Astrophysics Experiment I

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Outlook

- Motivation: Why do we care about Nuclear Astrophysics?
- Relevant quantities we want to measure: Cross sections, resonance energies and strengths, excitation energies, masses, reaction rates
- Examples of experiments: Stable beams, radioactive beams, direct measurements, indirect techniques
- 1st day lecture: Stable beam experiments
- 2nd day lecture: Radioactive beam experiments

Motivation

The understanding of stellar nucleosynthesis is one of the driving factors behind the study of nuclear astrophysics.

- What is the origin of the elements?
- How do stars form and evolve?
- What powers the stars?

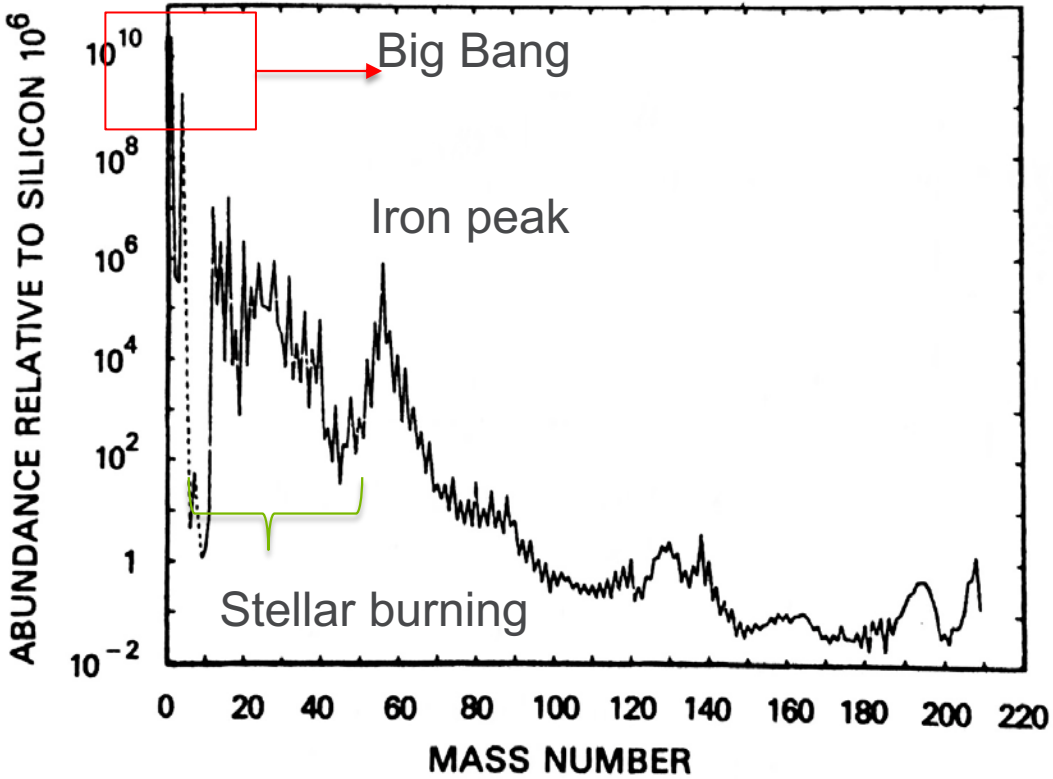
Credit: NASA, ESA, and the Hubble SM4 ERO Team

Nuclear Physics is Key!!

Cross sections, resonance energies and strengths, excitation energies, etc.

Solar system abundances

Clues to stellar processes

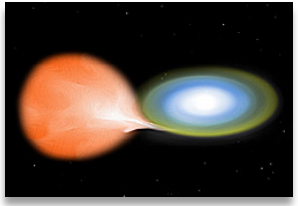


Cauldrons in the Cosmos. C. Rolfs and W. Rodney

- Fusion reactions beyond the iron peak becomes very unlikely

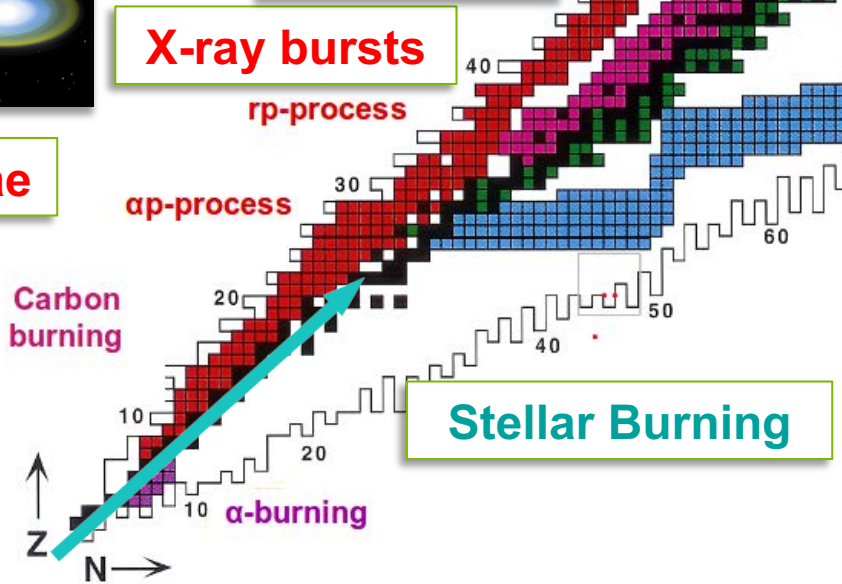
Nucleosynthesis Processes

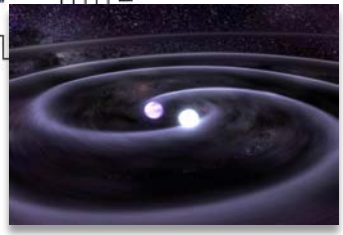
Red Giant Stars



X-ray bursts

Novae

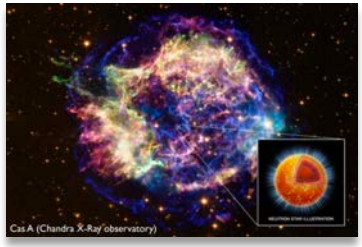




Neutron Star mergers

Weak r-process in NDW after CCSN

Stellar Burning



Modified image from:

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, **51** (2001)

How to proceed?

Focus on charge particle reactions

- Rates of some charged particle reactions, such as (p,γ), (α,n), (α,p) and (α,γ), are important input parameters for various astrophysical processes.

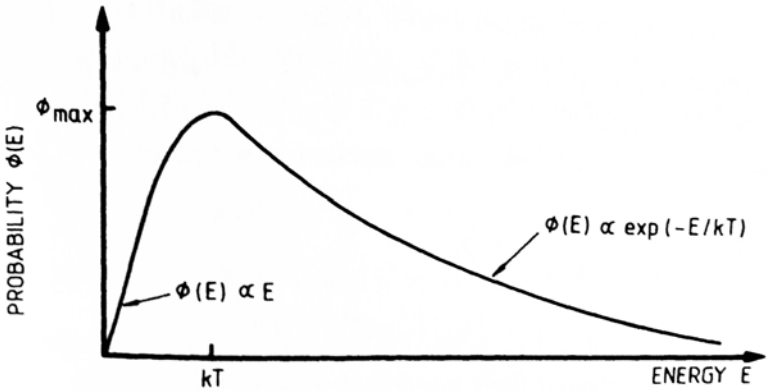
- Things to consider:
  - Type of reaction (detectors to use)
  - Backgrounds
  - Resonant reaction? Non resonant
  - Subthreshold states?
  - Direct capture
  - Level density
  - Cross sections estimate
  - Relevant concepts in Nuclear Astophysics

Reaction Rate

Maxwell-Boltzmann Distribution

In stellar plasma the velocity of the nuclei can be describe by:

$$\phi(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\left(\frac{mv^2}{2kT}\right)}$$



Cauldrons in the Cosmos. C. Rolfs and W. Rodney

Reaction rate per particle pair of interacting nuclei X and Y

$$\langle \sigma v \rangle = \iint_0^\infty \phi(v_x)\phi(v_y)\sigma(v)dv_x dv_y$$

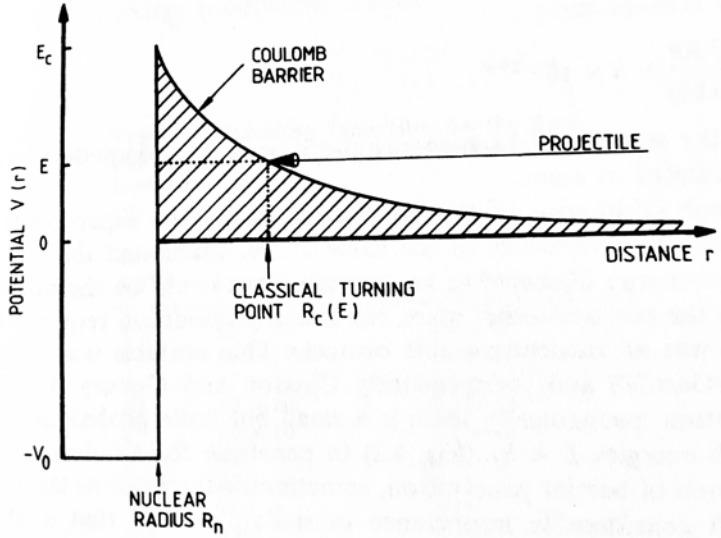
Using reduced mass and center-of-mass energy:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty \sigma(E) E e^{-\left(\frac{E}{kT}\right)} dE$$

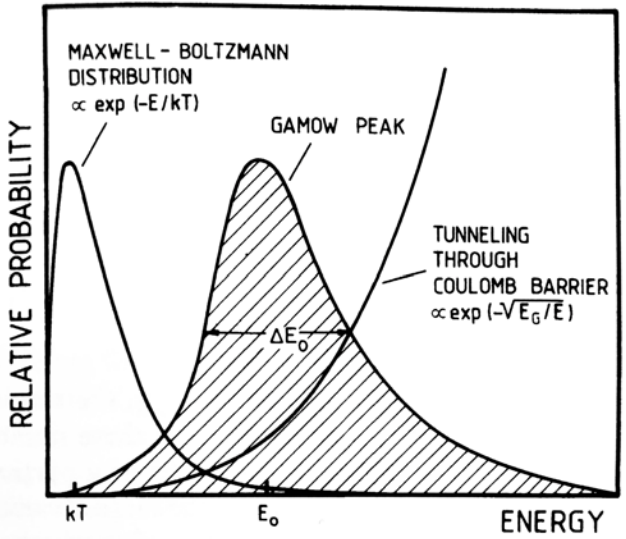
Gamow window

Charge particle reactions

Nuclear and Coulomb potentials



Narrow energy window for a given stellar temperature



Figures from Cauldrons in the Cosmos. C. Rolfs and W. Rodney

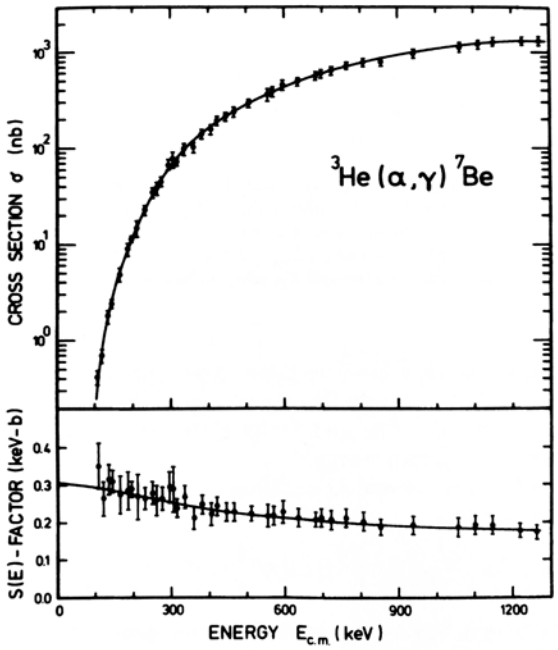
S-Factor

Nonresonant reaction

- Cross sections varies smoothly at high energies
- Drops quickly at low energy due to Coulomb barrier

$$\sigma\,(E) = \frac{1}{E}\,e^{-2\pi\eta}S(E)$$

Sommerfeld parameter: $$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$



Cauldrons in the Cosmos. C. Rolfs and W. Rodney

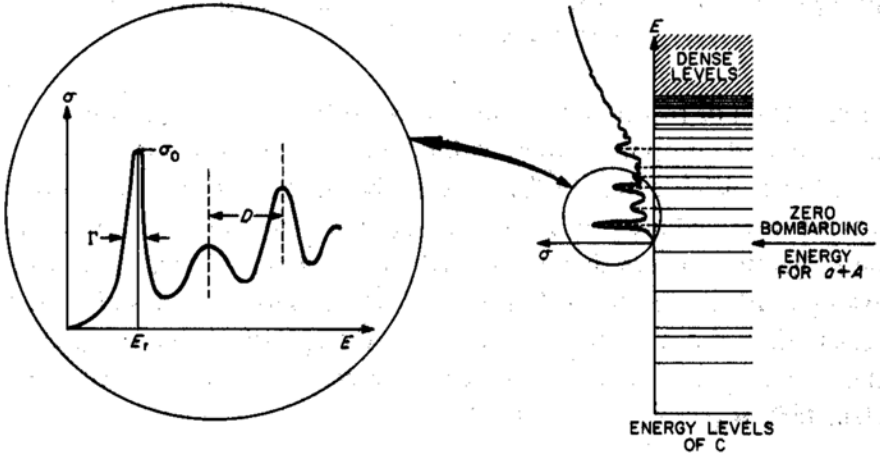
Narrow resonances

Single level resonance

Breit-Wigner resonance: $$\sigma(E) = \pi\lambda^2 \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_a \Gamma_b}{(E-E_r)^2 + (\Gamma/2)^2}$$

Total with is the sum of all the partial widths of open channels

$$\Gamma = \Gamma_a + \Gamma_b + \cdots$$



Narrow resonances

Single level resonance

If $\Gamma \ll ER$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int_0^\infty \sigma(E) E e^{-\left(\frac{E}{kT}\right)}\, dE \longrightarrow \langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{\frac{3}{2}} \hbar(\omega\gamma)_R\, e^{-\left(\frac{E_R}{kT}\right)}$$

$$\omega\gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma}$$

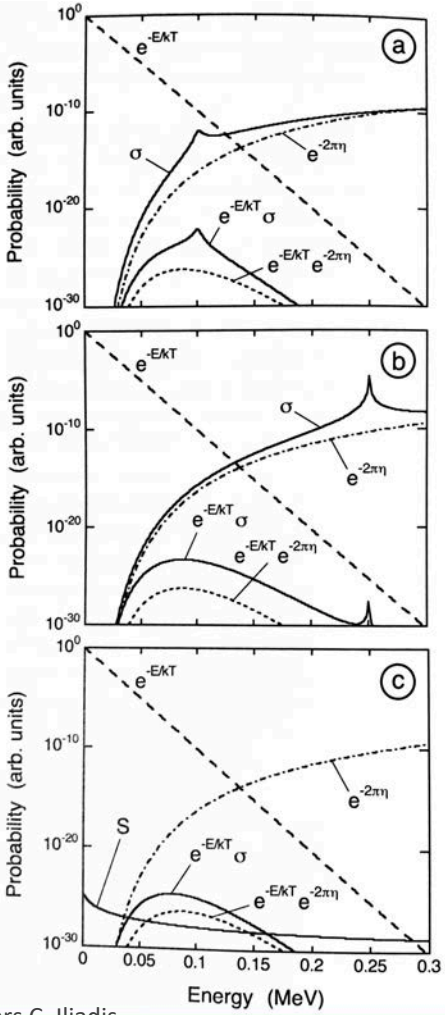
Strength of a resonance

$$\omega = \frac{2J+1}{(2J_1+1)(2J_2+1)}$$

Reaction rate depends on energy and resonance strength

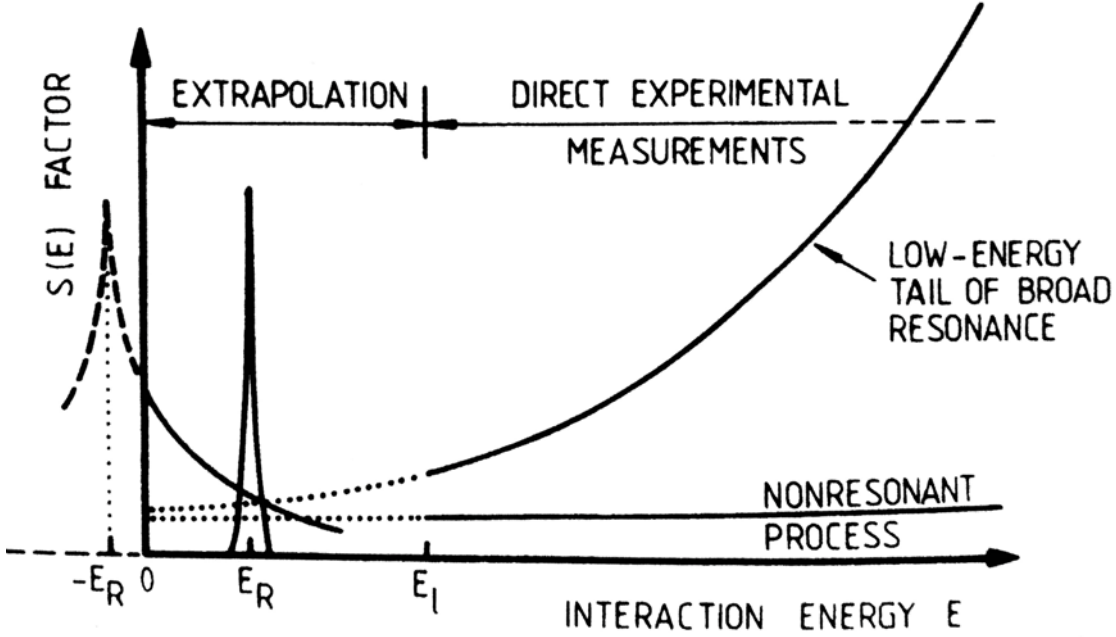
Broad-resonance reaction

- No longer energy independent
- Product of Maxwell Boltzmann distribution and cross section is a more complicated function
- Reaction rate has to be calculated numerically



Total reaction rate

Things to consider

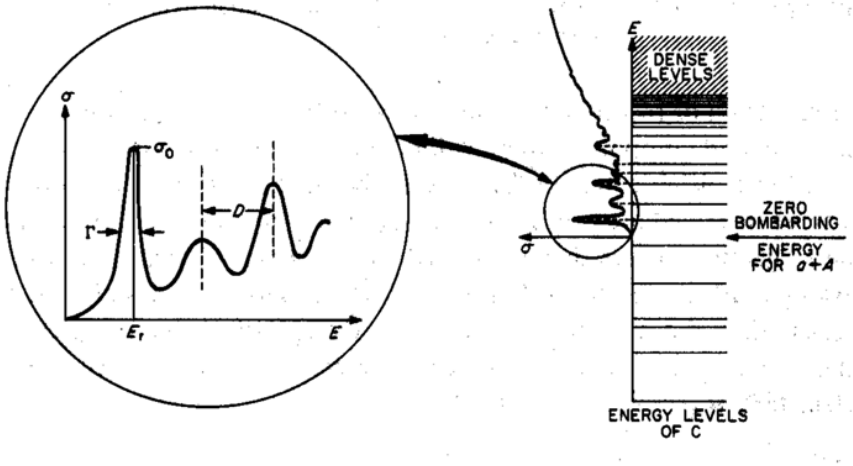


Cauldrons in the Cosmos. C. Rolfs and W. Rodney

Total reaction rates

Things to consider

- All contributions have to be considered
- For high density of states only energy-average cross section is relevant
- For resonance reaction, multi-channel multi-level cases, R-matrix could be used



HOW TO PROCEED?

Focus on charge particle reactions

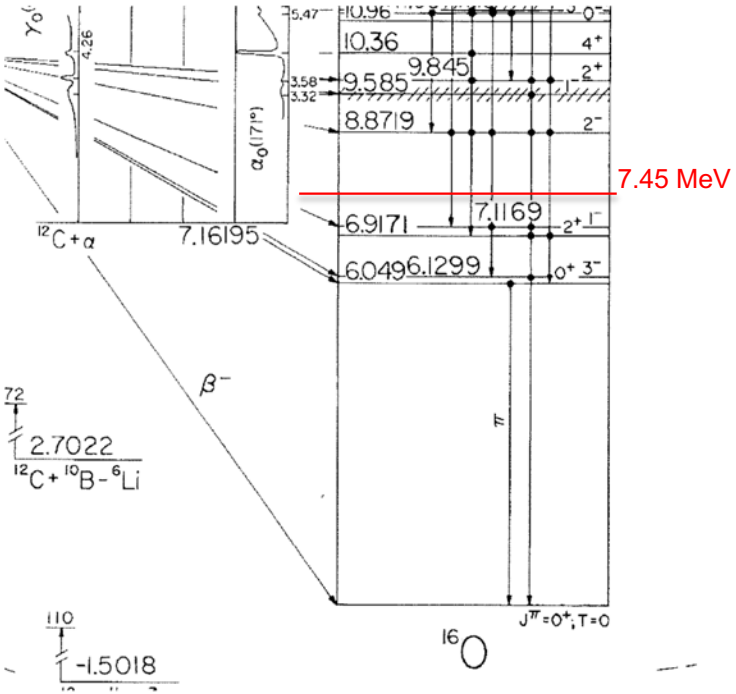
- Direct measurements are preferred. However, many astrophysically important reactions cannot be study directly at the relevant stellar energies due to small cross sections
- Indirect measurements can be performed to determine properties of states (such as spin, SF, energy, resonant strength etc.) and constraint the reaction rates
  - Transfer reactions
  - Asymptotic Normalization Coefficient (ANC),
  - Trojan Horse Method (THM)
  - Coulomb Dissociation Method,
  - charge-exchange reactions
  - Time inverse reactions
  - Mirror symmetry
- Combination of direct and indirect measurements

EXAMPLES OF REAL EXPERIMENTS WITH STABLE BEAMS

The $^{12}C(\alpha,\gamma)^{16}O$ reaction

- The $^{12}C(\alpha,\gamma)^{16}O$ is considered the most important reaction in nuclear astrophysics ("holy grail")
- In the stage of helium burning process the helium nuclei will begin to fuse creating ^{12}C and ^{16}O
  - 3-α capture
  - $^{12}C(\alpha,\gamma)^{16}O$
- The ratio of $^{12}C/^{16}O$ will determine the evolution of the star and subsequent synthesis of heavier elements
- This ratio has a large dependence on the $^{12}C(\alpha,\gamma)^{16}O$

The $^{12}C(\alpha,\gamma)^{16}O$ reaction



- Gamow peak is at 300 keV (cross section ~ 10^{-17} b)
- No resonances in the energy region of interest!
- Interferences between broad overlapping resonances and nonresonant reaction components

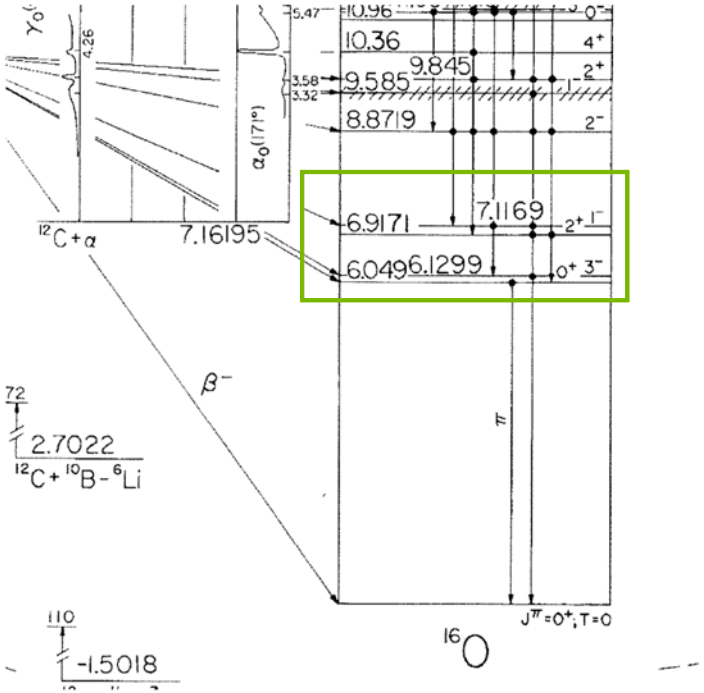
The $^{12}C(\alpha,\gamma)^{16}O$ reaction

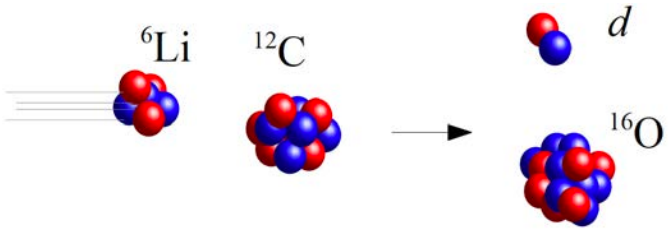
Things to consider

- Very challenging!
- Can’t be measure directly
- Reaction rate needs to be known to an uncertainty of 10%
- Combination of high energy measurements and indirect measurements to study subthreshold states are needed

α-transfer reaction at sub-Coulomb energies

ANC of sub-threshold states to constrain the $^{12}C(\alpha,\gamma)^{16}O$ reaction





- It is possible to extract the ANC from a direct alpha transfer reaction in which an alpha cluster is transferred to the nucleus
- ANC defines the amplitude of the tail of the radial overlap function

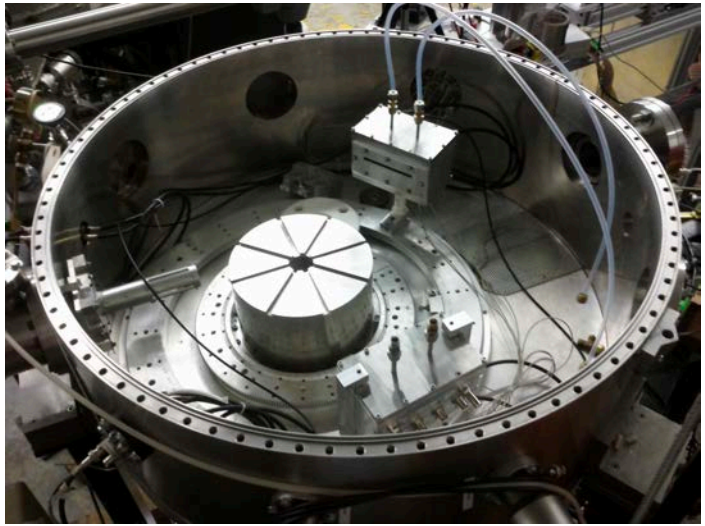
$$I^{c}_{abl_cj_c}(r) \rightarrow C^{c}_{abl_cj_c}\frac{W_{-\eta_c,l_c+1/2}(2\kappa_{ab}r)}{r} \quad , \; r > R_N$$

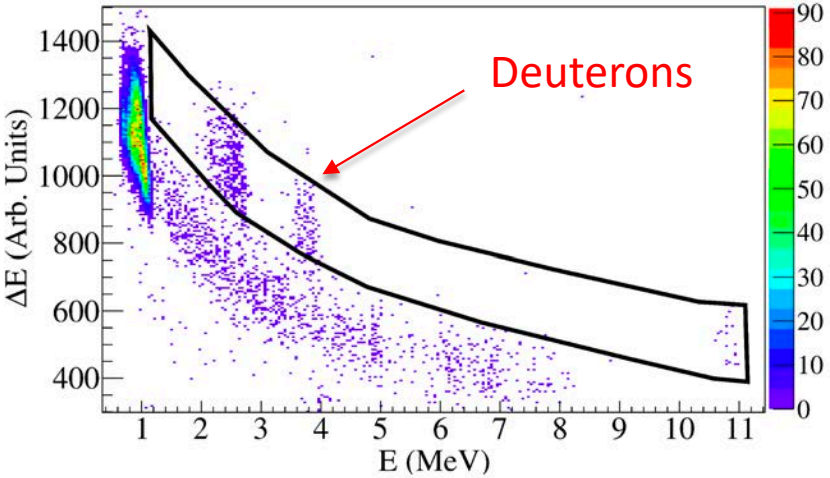
ANC

α-transfer reaction at sub-coulomb energies

ANC of sub-threshold states to constrain the $^{12}C(\alpha,\gamma)^{16}O$ reaction

- Experiment Performed at Florida State University
- ^{12}C energies: 9, 7 and 5 MeV
- Measure deuterons in DE telescopes (Proportional counter wire +silicon detectors)

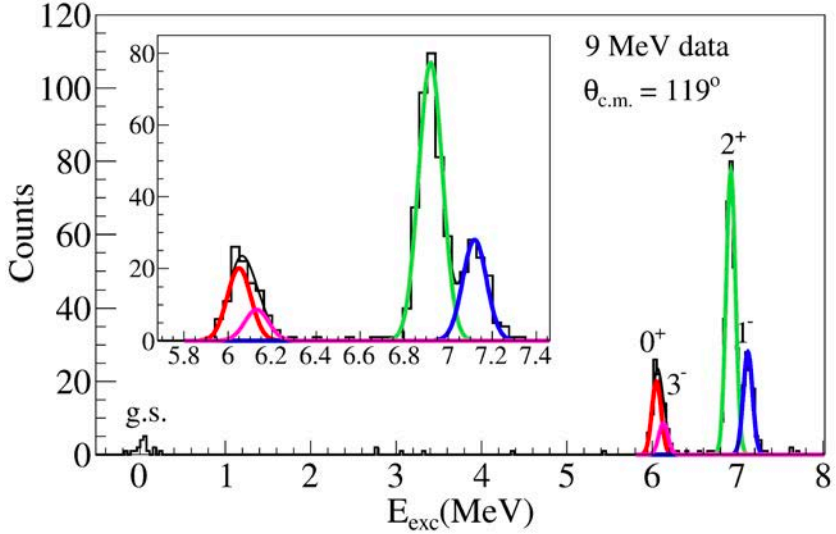


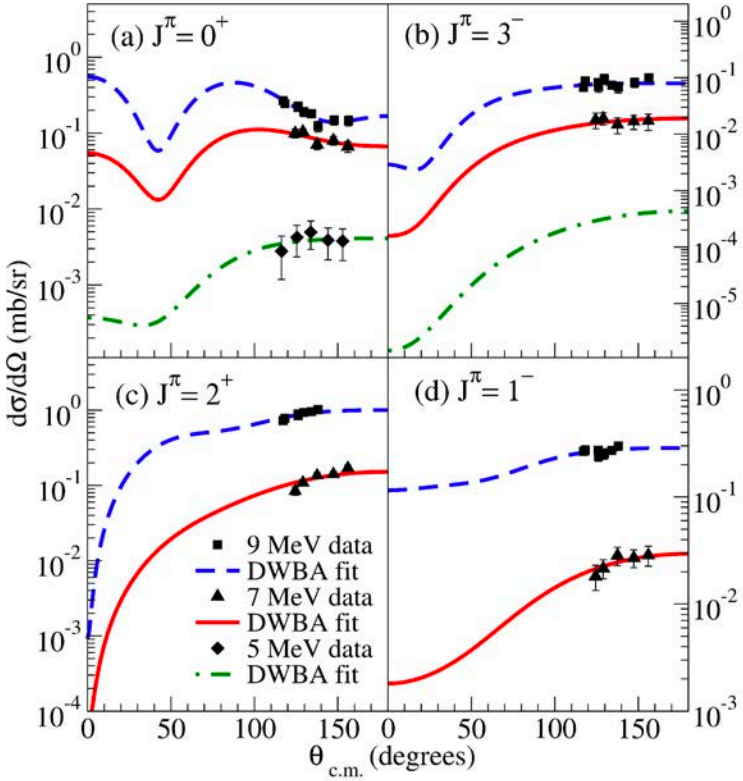


α-transfer reaction at sub-Coulomb energies

ANC of sub-threshold states to constrain the $^{12}C(\alpha,\gamma)^{16}O$ reaction

- Measure deuterons angular distributions
- Distorted wave Born approximation





α-transfer reaction at sub-Coulomb energies

ANC of sub-threshold states to constrain the $^{12}C(\alpha,\gamma)^{16}O$ reaction

- Extract the ANCs
- Uncertainties related to the contribution of 0^+ and 3^- were dramatically reduced.

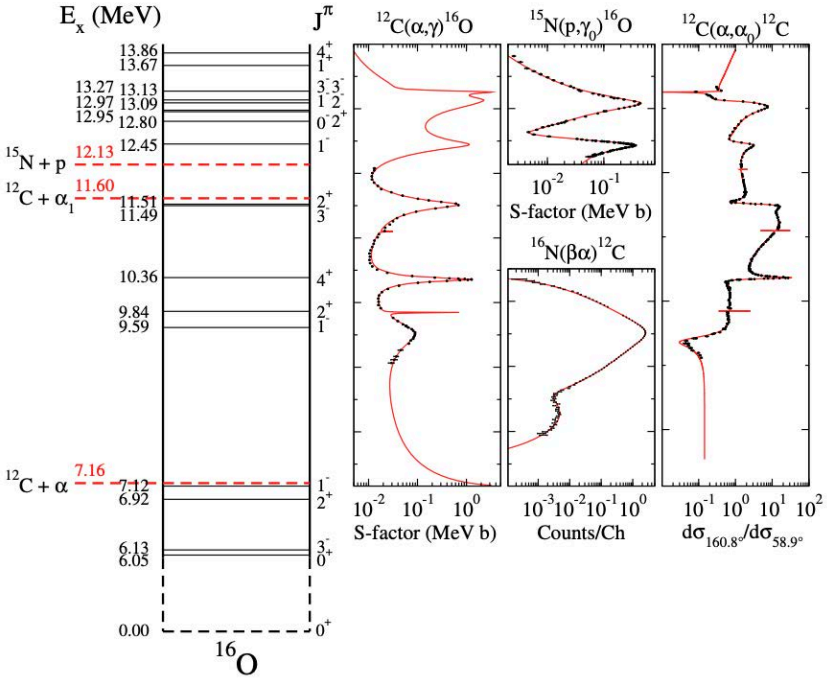
$(C^{^{16}O(0^+)}_{\alpha-^{12}C})^2$ (10^6 fm^{-1})	$(C^{^{16}O(3^-)}_{\alpha-^{12}C})^2$ (10^4 fm^{-1})	$(C^{^{16}O(2^+)}_{\alpha-^{12}C})^2$ (10^{10} fm^{-1})	$(C^{^{16}O(1^-)}_{\alpha-^{12}C})^2$ (10^{28} fm^{-1})	Ref.
...	...	2.07 ± 0.80	4.00 ± 1.38	[1]
...	...	1.29 ± 0.23	4.33 ± 0.84	[2]
...	...	$1.96^{+1.41}_{-1.27}$	3.48 ± 2.0	[3]
2.43 ± 0.30	1.93 ± 0.25	1.48 ± 0.16	4.39 ± 0.59	This work

M.L. Avila et al., Phys. Rev. Lett. 114, 071101 (2015)

The $^{12}C(\alpha,\gamma)^{16}O$ reaction

Recent review

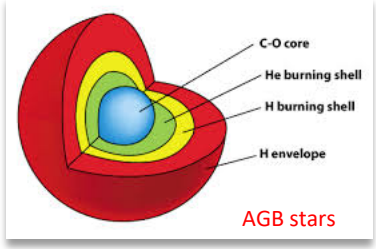
- Combination of indirect technique measurements such as β-delay α emission spectra of 16N and sub-Coulomb transfer
- Direct data in R-matrix analysis reduced the uncertainty for S(300 keV) to ≈20%

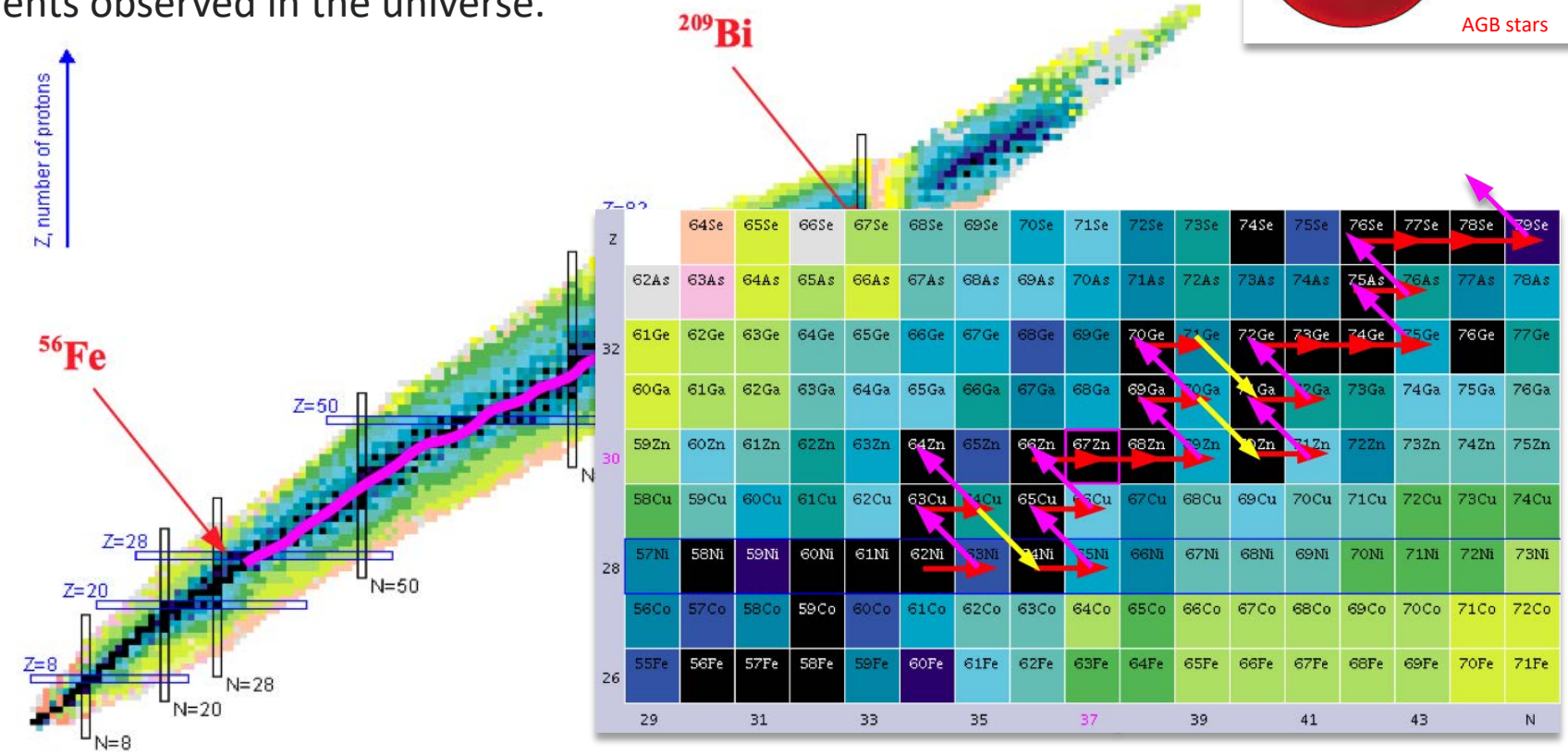


R. J. DeBoer et al., Rev. Mod. Phys., Vol. 89, No. 3, (2017)

The $^{13}C(\alpha,n)^{16}O$ reaction and the s-process

- The s-process is responsible for nearly half of the heavy elements observed in the universe.





s-process

Where are the neutrons coming from?

Two main neutron sources reactions:

$^{13}C(\alpha,n)^{16}O$

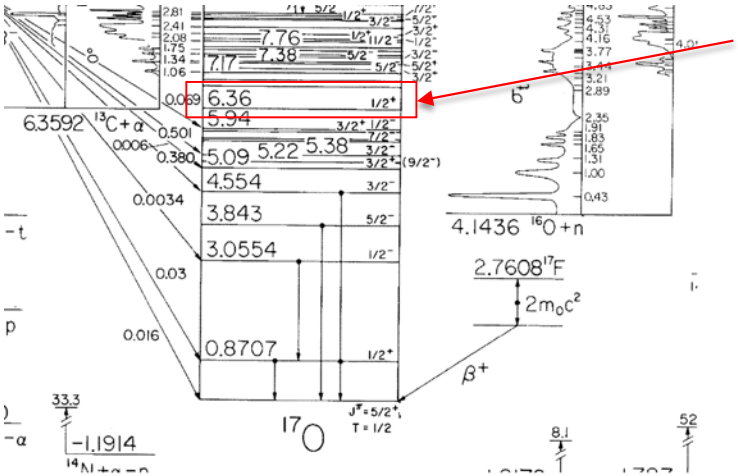
$^{22}Ne(\alpha,n)^{25}Mg$

- Large experimental efforts for the measurement of these two reactions (direct and indirect studies).
- Including experiments at underground laboratories such as LUNA

The $^{13}C(\alpha,n)^{16}O$ reaction

α-transfer reaction at sub-Coulomb energies

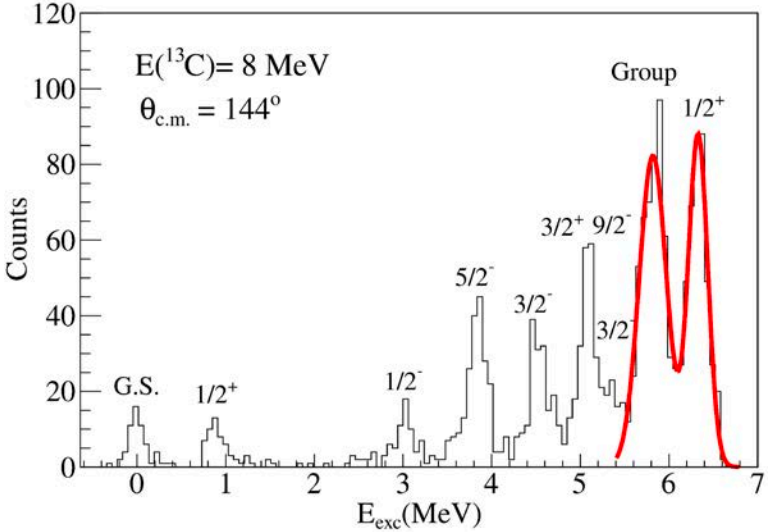
- The $^{13}C(\alpha,n)$ cross section at the Gamow window is dominated by the tails of the near α threshold states
- Partial Γ_α width of the 1/2+ state at 6.356 MeV in ^{17}O is the main source of the $^{13}C(\alpha,n)$ reaction rate uncertainty

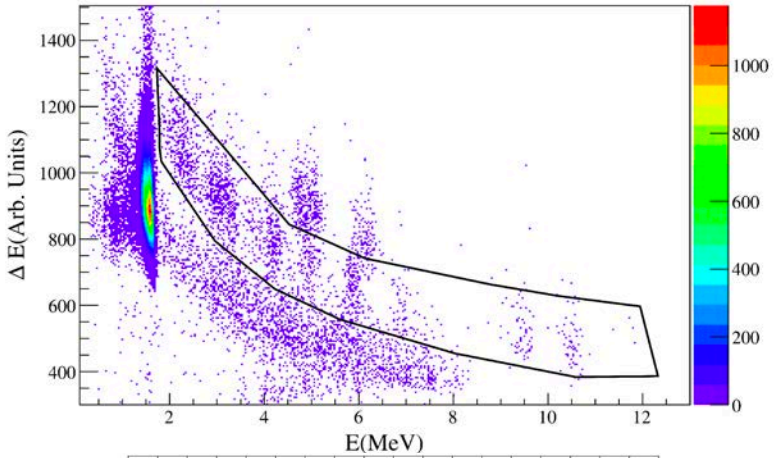


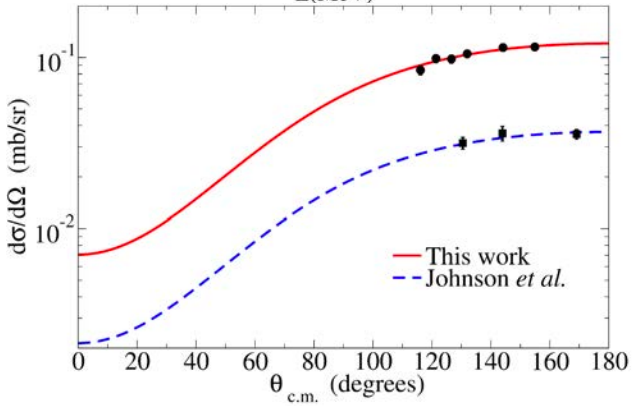
Only bound by 3 keV!

The $^{13}C(\alpha,n)^{16}O$ reaction

α-transfer reaction at sub-Coulomb energies



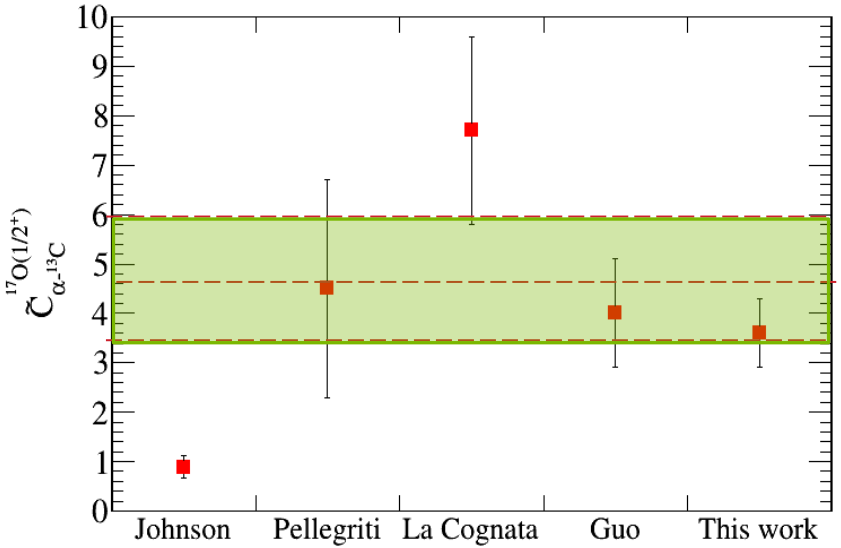




Coulomb modified ANC of .+ resonance is 3.6±0.7 fm-1

The $^{13}C(\alpha,n)^{16}O$ reaction

Summary of measurements for the subthreshold state

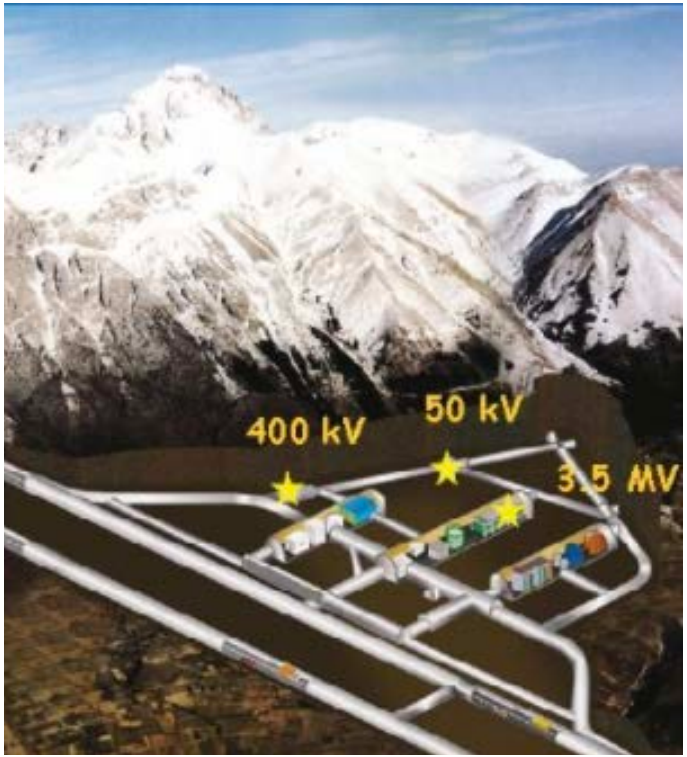


$(\tilde{C}^{17O(1/2+)}_{\alpha-13C})^2 fm^{-1}$	S_α	Ref.
	0.01	S. Kubono
0.89 ± 0.23		E. D. Johnson
	0.36–0.40	N. Keeley
4.5 ± 2.2	0.29 ± 0.11	M. G. Pellegriti
$7.7 \pm 0.3_{stat}{}^{+1.6}_{-1.5\,norm}$		M. L. Cognata
4.0 ± 1.1	0.37 ± 0.12	B. Guo
3.6 ± 0.7		M.L. Avila

Reasonable agreement after removing Kubono and Johnson!

The $^{13}C(\alpha,n)^{16}O$ reaction

Laboratory for Underground Nuclear Astrophysics (LUNA)

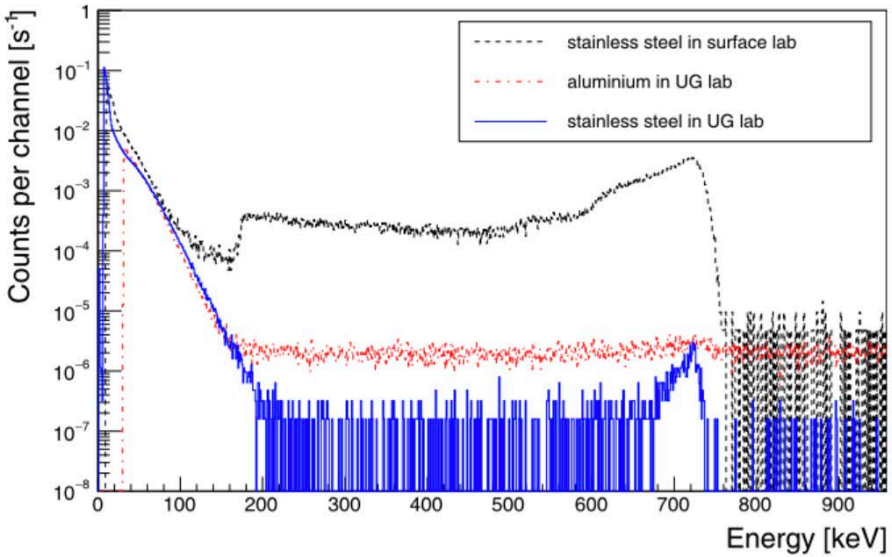


Laboratori Nazionali del Gran Sasso (LNGS) in Italy

- 1400 meters of rock
- Shielded from cosmic rays
- 3 orders of magnitude reduction Gamma rays

The $^{13}C(\alpha,n)^{16}O$ reaction

Laboratory for Underground Nuclear Astrophysics (LUNA)

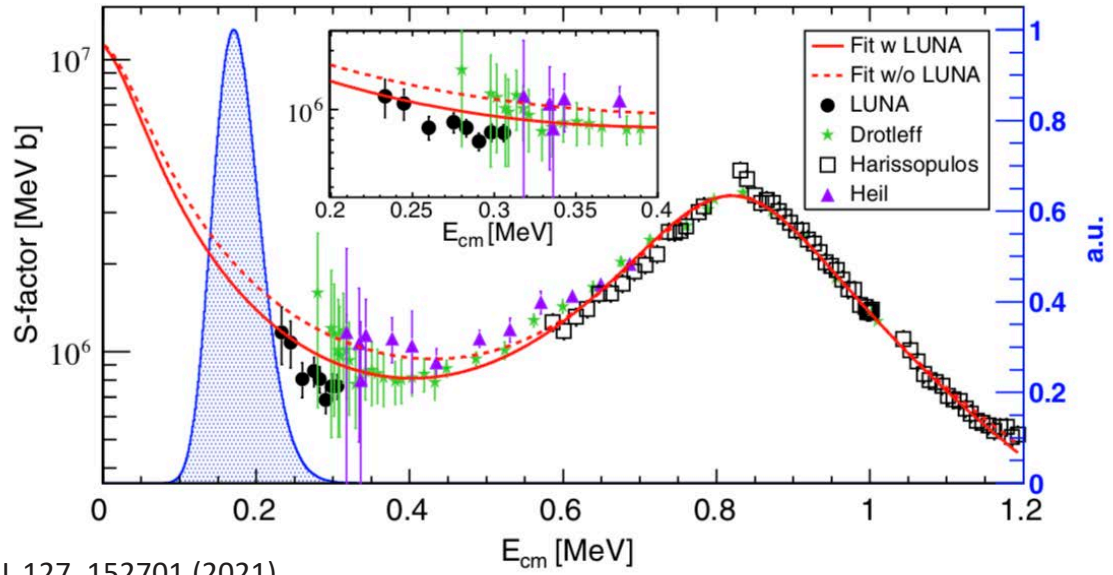


Comparison of background spectra of bare ^{3}He counters acquired on the surface and in the underground laboratory (UG lab) using single counters

L. Csedreki et al., Nucl. Inst. and Meth., A 994 (2021) 165081

The $^{13}C(\alpha,n)^{16}O$ reaction

Direct measurement at LUNA



G. F. Ciani, PRL 127, 152701 (2021)

- Improved calculation of the reaction rate based on direct data inside of the Gamow window and R-Matrix fit

LUNA

Other experiments

Past experiments

At the LUNA 50 kV accelerator:

- $^{3}He(^{3}He,2p)^{4}He$
- d(3He,p)4He
- d(d,p)t
- $D(p,\gamma)^{3}He$

At the LUNA-400 kV accelerator:

- $^{3}He(\alpha,\gamma)^{7}Be$
- $^{14}N(p,\gamma)^{15}O$
- $^{15}N(p,\gamma)^{16}O$
- $^{25}Mg(p,\gamma)^{26}Al$
- $^{2}H(\alpha,\gamma)^{6}Li$
- $^{17}O(p,\gamma)^{18}F$
- $^{17}O(p,\alpha)^{14}N$
- $^{22}Ne(p,\gamma)^{23}Na$
- $^{18}O(p,\alpha)^{14}N$

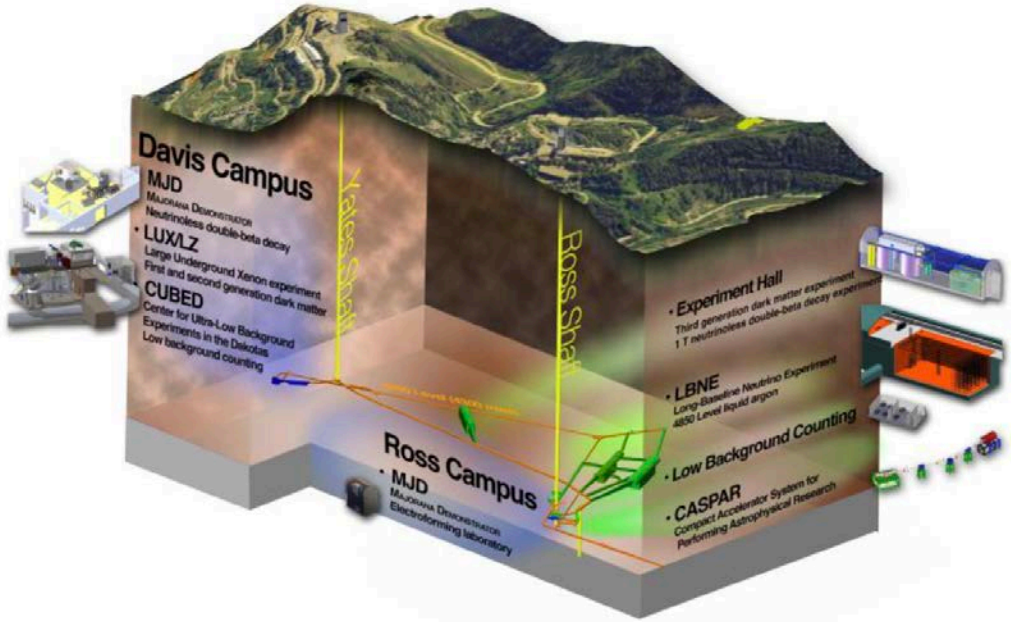
Future experiments

Scientific program:

- $^{14}N(p,\gamma)^{15}O$
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$
- $^{12}C+^{12}C$

Underground laboratory in the US

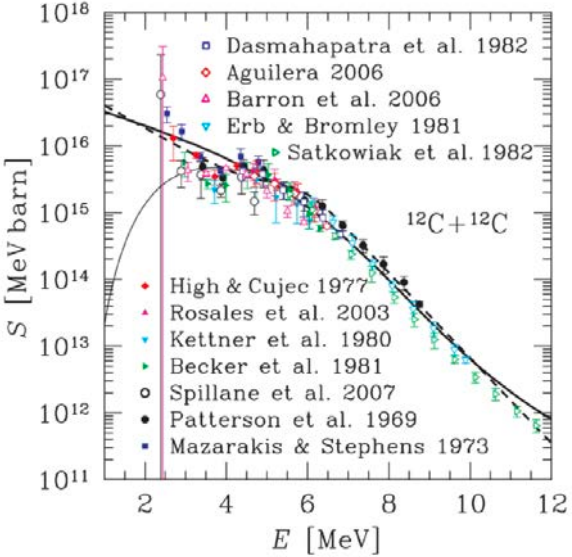
CASPAR

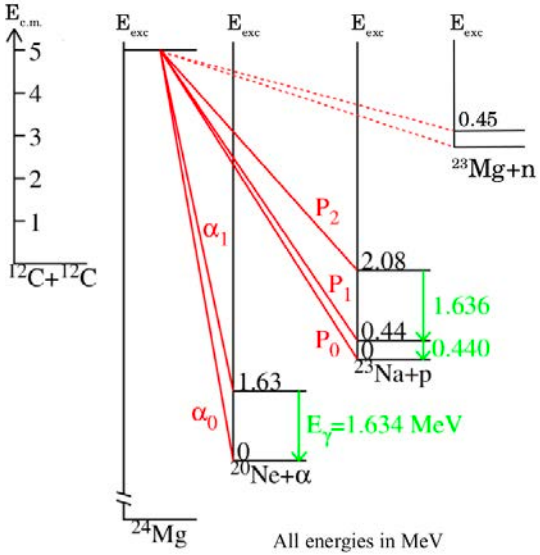


- The Compact Accelerator System for Performing Astrophysical Research
- Located at the Sanford Underground Research Facility (SURF) in Lead, South Dakota.
- 4850 ft (1478 m) underground

The $^{12}C+^{12}C$ reaction

- Important in Type Ia supernovae, X-ray superbursts. Primary route for the production of heavy elements.





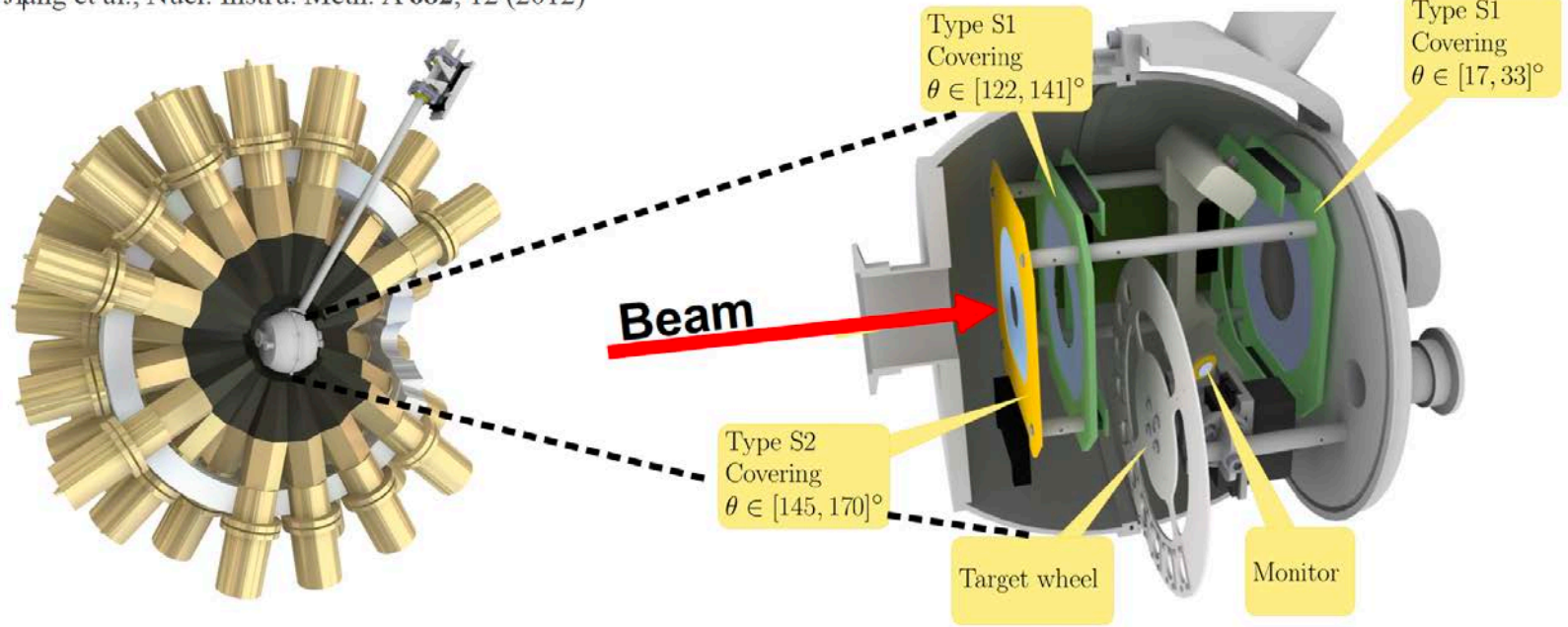
- Large uncertainties (background, target impurities)
- Background associated with singles can be removed if the charged particles and γ rays are measured in coincidence.

The $^{12}C+^{12}C$ reaction

Coincidence technique of γ rays and charge particles at ANL

Gammasphere + silicon arrays

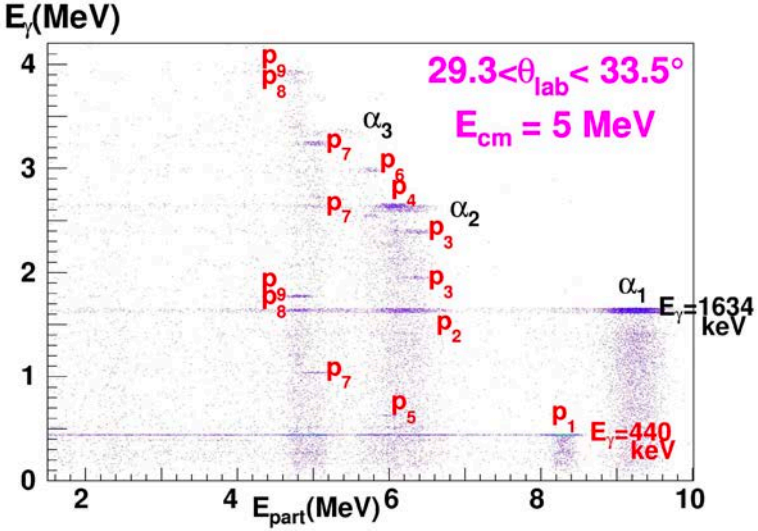
C.L. Jiang et al., Nucl. Instru. Meth. A **682**, 12 (2012)

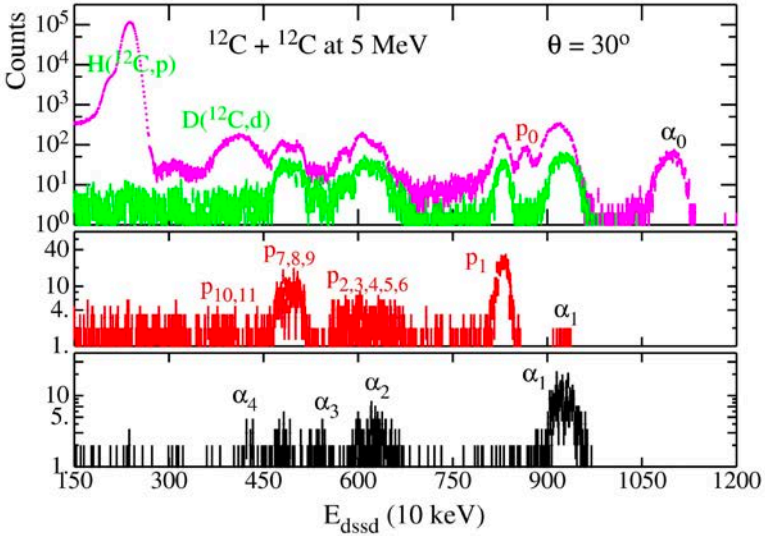


The $^{12}C+^{12}C$ reaction

Coincidence technique of γ rays and charge particles at ANL

$E_{c.m.}$=5 MeV

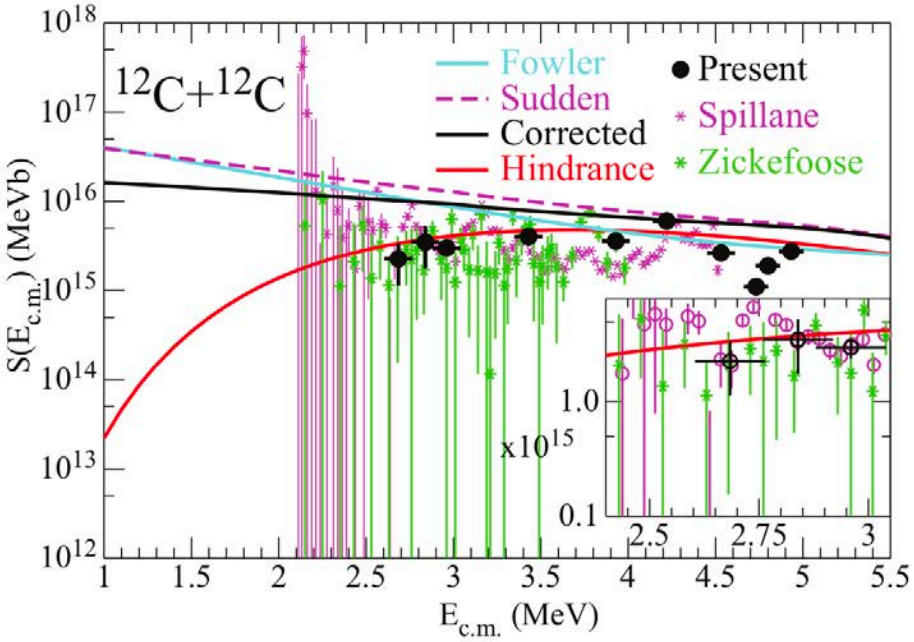




Coincidence: *with any γ*
with E_γ=440
with E_γ=1634

The $^{12}C+^{12}C$ reaction

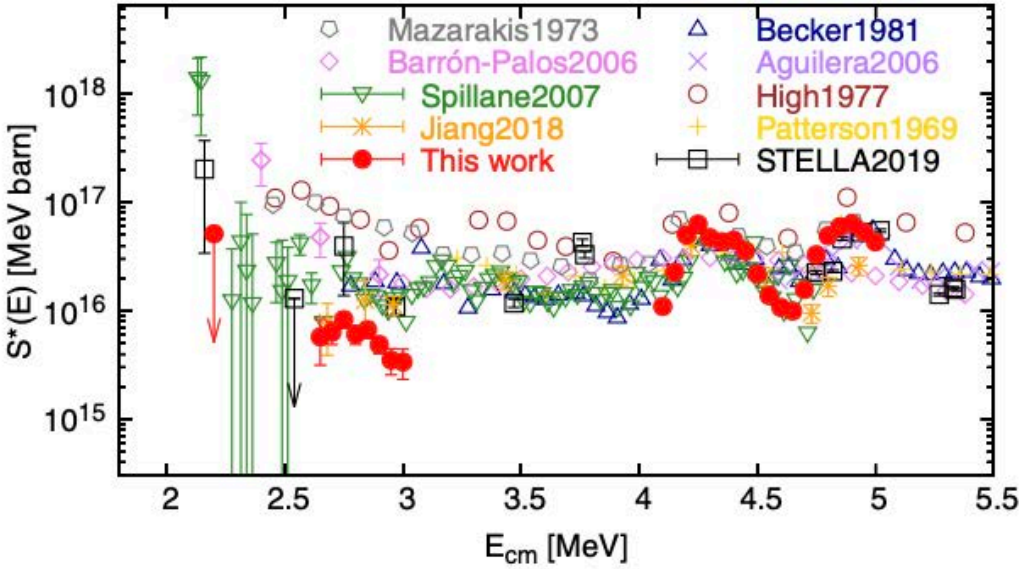
Coincidence technique of γ rays and charge particles at ANL



C.L. Jiang et al., PRC 97, 012801 R(2018)

The $^{12}C+^{12}C$ reaction

Coincidence technique of γ rays and charge particles at ND



W.P. Tan et al., Phys. Rev. Lett. 124, 192702 (2020)

QUESTIONS?